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Expanded Polystyrene Re-Expansion Analysis Following Impact Compression

By Mark S. Adams
Frederick Brozoski
Katie Logsdon

United States Army Aeromedical Research Laboratory

Survival Analysis Division
Injury Biomechanics Division

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Adams, Mark S.
Brozoski, Fred
Logsdon, Katie

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14. ABSTRACT
Post-accident aviator helmet analysis involves a visual inspection of damage to the energy absorbing liner. U.S. Army aviator helmets use expanded bead polystyrene (EPS) of various densities for the energy attenuating liner (EAL) material. This material is known to rebound after compression, and the rebound properties must be understood in order to estimate the actual EAL compression sustained in an impact. This report describes the method and results of compression and rebound tests on the four polystyrene densities, illustrating the results in the form of regression curves. A high degree of linear correlation was found between initial compression and the final thickness ratio of the EPS material. Rebound was essentially complete 24 hours after compression. The results will be used also when examining post-accident helmet damage to help determine helmet impact forces experienced in survivable helicopter accidents.

15. SUBJECT TERMS
Expanded polystyrene, EPS, Helmet, Helmet impact damage, energy attenuating liner, EAL

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Introduction

Expanded bead polystyrene (EPS) is widely used as the primary energy absorbing material in aircrew and motorcycle protective helmets; EPS has excellent performance and is lightweight and low cost. Whilst the outer shell of a helmet contributes to energy attenuation through deformation and distributing impact loads over a large area, the EPS inner layer is designed to absorb impact energy and minimize the load transmitted to the skull of the wearer. A critical property of an EPS foam liner is its density, as the yielding stress at which the foam crushes is directly related to density (Gibson and Ashby, 2001). The density and thickness of the EPS layer in a helmet will depend on the impact protection requirements. Increased density allows better energy dissipation at the expense of higher transferred loads, whereas increased thickness can increase absorbable impact energy at the expense of EPS thickness (Di Landro, Sala, and Olivieri, 2002). Foam thicknesses between 3.0 and 4.0 centimeters (cm), and densities from 0.02 and 0.1 grams per cubic centimeter (g/cm^3) are commonly employed in current aircrew and motorcycle helmet designs.

The amount of energy that the foam absorbs is equal to the reduction of foam volume due to the crushing multiplied by the stress under which the foam crushes (Cernicchi, Galvanetto, and Iannucci, 2008). The compressive behavior of typical low-density EPS used in aviation helmets shows linear elasticity at low stresses, followed by a plastic deformation plateau, and a final densification where stress rises steeply. The linear phase holds for small strains (3 to 5 percent, whilst the plateau holds up to 70 percent strains approximately, during which there is progressive, non-uniform buckling of cells and bead walls, contributing to absorbing energy (Di Landro et al., 2002). At larger compressive strains (> 70 percent), the EPS foam cells collapse and opposing cells are crushed together, resulting in a steep rise in the stress-strain curve and little or no energy attenuation. When compressive stresses are removed, EPS foam will partially re-expand.

Temperature can affect EPS performance; across a range from -17 to +43 degrees Centigrade (C), no difference in energy attenuation performance was recorded with low-density (0.016 g/cm^3) EPS (Marcondes, Hatton, Graham, and Schueneman, 2003). At a higher temperature of 60 degrees C, changes in relative humidity from 40 percent to 85 percent resulted in decreased yield stress at higher humidity levels, resulting in lower stress levels for a given strain (Liu, Chang, Fan, and Hsu, 2003).

The two primary rotary-wing aviation helmets in use with the U.S. Army are the Head Gear Unit No. 56/Personal Aircrew Integrated Helmet System (HGU-56/P AIHS), and the Integrated Helmet and Display Sighting System (IHADSS) helmet used in the AH-64 Apache. Both helmets rely on an EPS energy absorbing liner (EAL) inside the outer shell for the majority of the energy absorption. The IHADSS has a single-density liner, measuring 0.05 g/cm^3, and the liner thickness varies according to helmet region, with a maximum thickness of approximately 1.54 cm. The HGU-56/P AIHS has an EAL composed of two sections, with higher densities in the frontal area. Three densities (0.02, 0.035, and 0.04 g/cm^3) and various thicknesses of EPS up to 3.8 cm are used to ensure similar impact protection for all six available helmet sizes (appendix A).

Since 1972, the U.S. Army Aeromedical Research Laboratory (USAARL) has conducted post-accident analysis of rotary-wing helmet performance, in an effort to enhance aviator head injury protection in survivable accidents. U.S. Army helicopter helmet standards have evolved during that period as a result of periodic retrospective reviews of helmet performance in accidents (Slobodnik, 1980; Vrynwy-Jones, Lanoue, and Pritts, 1988; Palmer, 1991). Post-accident analysis involves a thorough examination of the shell, and removal and examination of the EPS to record the size, shape, and depth of impact compressions. To determine the percentage of EPS compression, the maximum depth of compression is measured and compared with the thickness of an undamaged liner at the same location. Unfortunately, this does not provide adequate information about the forces applied to the helmet during an impact, thereby limiting the understanding of injury mechanisms.

Laboratory reconstruction of the helmet damage is an established technique for quantifying the force levels experienced by helmets during accidents, (Slobodnik, 1979; Caine, Bain-Ungerson, Schochat, and Marom, 1991). However, as already described, EPS foam will re-expand after initial compression. Therefore, in order to reconstruct impact damage as closely as possible, it is essential to understand the relationship between initial EPS foam compression and re-expansion. Earlier work (Slobodnik and Nelson, 1977) on the higher density (0.08 g/cm^3) EAL used in the Sound Protective Helmet No. 4 (SPH-4) showed a linear relationship between initial EPS compression and the amount of re-expansion; Slobodnik and Nelson (1977) also showed that re-expansion was complete 72 hours after compression and that temperature did not affect the results.

Although EPS foam material performance can be affected by high local temperature and humidity as discussed above (Liu et al., 2003), helmets worn in survivable accidents are usually recovered from the accident site at the same time as the surviving crew. As such, they are then subjected to ambient (room) temperature conditions rarely more than 2 hours after an accident. Therefore, although the amount of EPS compression might be influenced by ambient climatic conditions at the time of impact, re-expansion will most often occur in room temperature conditions. Furthermore, testing of low-density EPS foam similar to that used in the HGU-56/P AIHS conducted by Marcondes et al. (2003) would suggest that a broad range temperature will have no effect on EPS performance.

Objective

The current investigation determines, under ambient (room) temperature conditions, the time-dependent re-expansion characteristics of the EPS material used in the EALs of the HGU-56/P AIHS and the IHADSS helmets. The data at ambient temperature will be of most practical use in post-accident analysis, as discussed above. Future testing will be conducted after hot conditioning to 50 degrees C, in accordance with Military Standard 1680-ALSE-101 (1995). The data from this and the future high temperature study will be used during reconstructive helmet drop tests to determine the delay required before the damage to the EAL should be examined. This testing will not be used to estimate the input energy required to cause permanent deformation of the EPS foam.

Materials and methods

EPS energy attenuating liners typically have complex geometric shapes. However, the use of flat sheets of polystyrene facilitated the sample preparation. Sheets of EPS in densities of 0.02, 0.035, 0.04, and 0.05 g/cm^3 were procured from the Gentex® Corporation (Carbondale, Pennsylvania). Although the target densities are as listed, due to manufacturing tolerances, the density of each EPS sample can be up to 0.004 g/cm^3 higher than stated. Since the compression and re-expansion properties of this polystyrene are independent of thickness, 2.54-cm-thick sheets were selected for use in this study. Samples of 3.8 cm diameter polystyrene were cut using a bore cutter bit attached to a drill press. The baseline thickness (BT) of the polystyrene samples was measured using a Starrett® model 675GJ dial comparator, accurate to within 0.001 cm, mounted to a granite base.

Quasi-static compression of each sample was performed using an Instron® Materials Test System, model 4411. The Instron® 4411 consists of two main components: a control console and a moveable crosshead, which is displaced by two vertical worm gears. The system is capable of applying a compressive load of up to 4,448 newtons (N) at crosshead speeds of up to 50 cm per minute. A 4,448 N piezoelectric load cell is attached to the crosshead to measure compressive force. Crosshead motion relative to the stationary frame was recorded.

Using a preset stopping distance on the Instron® 4411, three samples of each EPS density were compressed to 85, 70, 55, 40, 25, and 10 percent of baseline thickness (percent BT). All tests were performed according to a free-volume method allowing radial expansion during compression. The highest density 0.05 g/cm^3 EPS samples were compressed to a maximum of 25 percent due to the Instron® 4411 load limitations. The compression rate was 5 cm per minute. Postcompression thickness (PCT) was determined using the Starrett® 675GJ at 24-hour intervals up to 72 hours. All testing was conducted at ambient (room) temperature.

Results

Thickness measurements of the polystyrene samples taken before and after compression are listed in appendix B. Mean data from the three samples was used to plot re-expansion over time as a percentage of PCT to BT (PCT/BT x 100) for the initial and subsequent 24-hour intervals up to 72 hours (figure 1). Re-expansion changes were observed at 24 hours with negligible changes in re-expansion at the 48- and 72-hour observations (appendix B). Re-expansion was linear with respect to initial compression with a density-dependent slope (figure 2). Equations relating re-expansion to initial compression for each density have been derived from the data in figure 2 (appendix C).

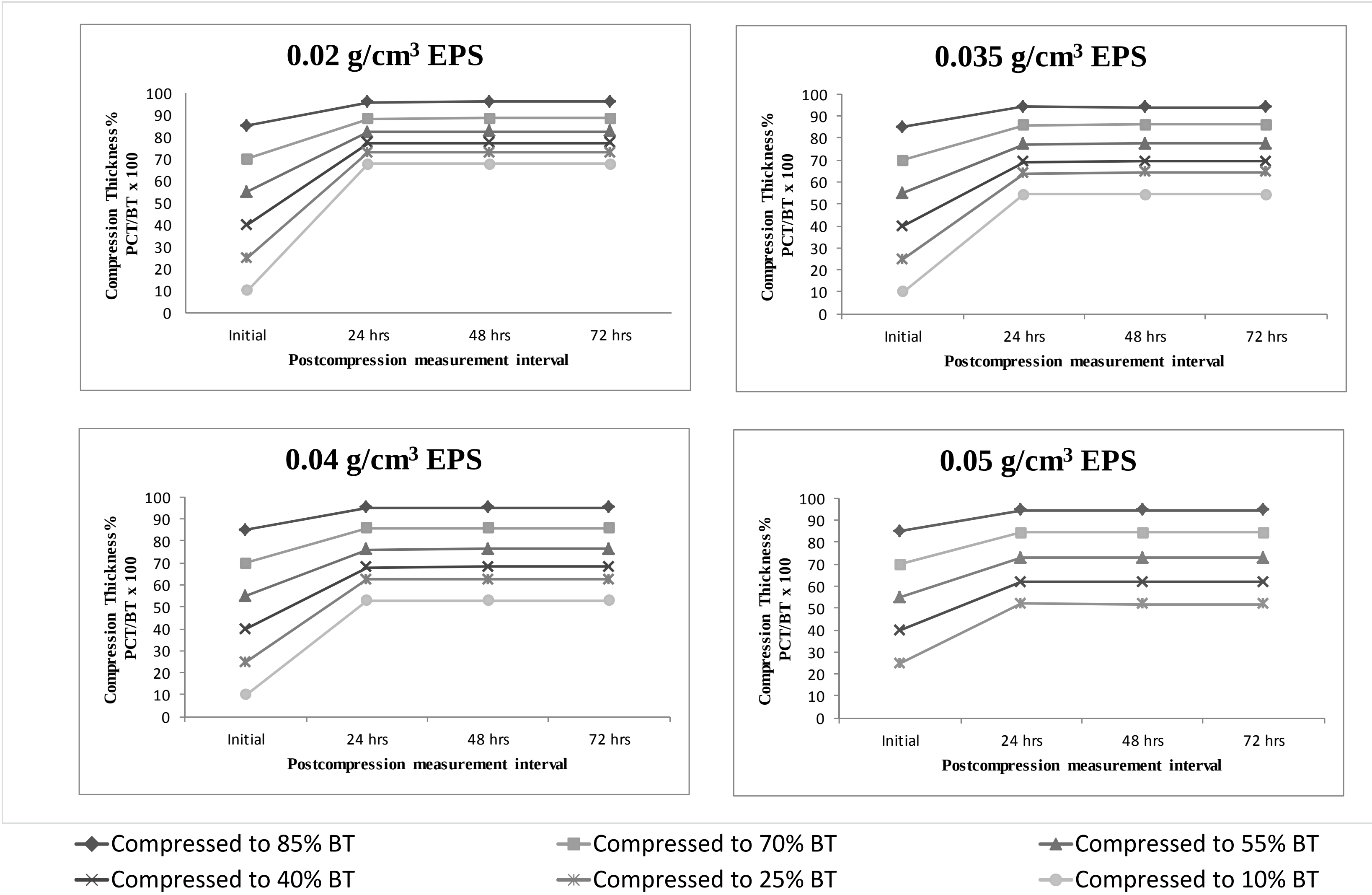

Figure 1. Mean EPS re-expansion against time. Compression of EPS of various densities and mean observed re-expansion assessed at 24-hour intervals postcompression up to 72 hours. The Instron® 4411 material test system could not generate sufficient force to compress the 0.05 g/cm^3 EPS foam to 10 percent BT. PCT = postcompression thickness; BT = baseline thickness.

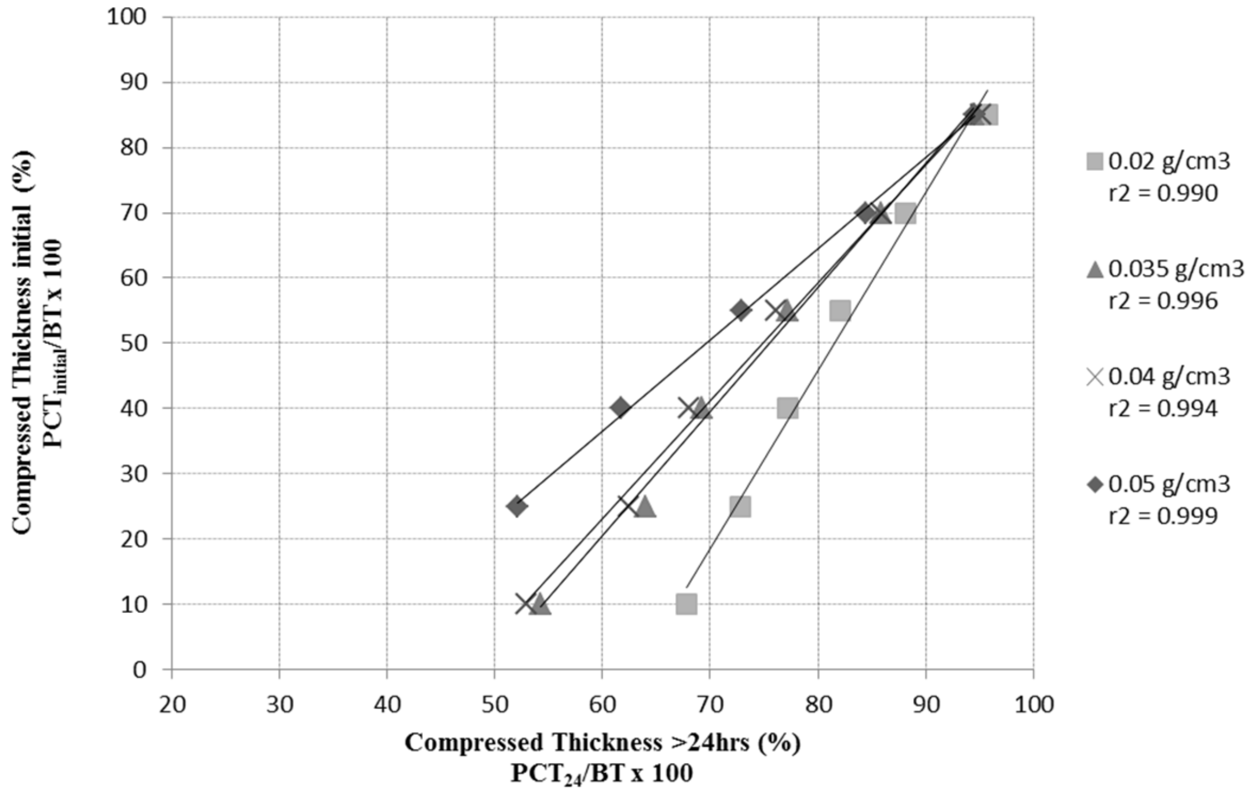

Figure 2. Derived graph from mean data to determine initial EPS compression thickness. Measurements taken on a sample after allowing >24 hours of expansion can be used to calculate the initial compression. The slope is a function of density with a common intercept at lower compression (85 percent of BT). PCT = postcompression thickness; BT = baseline thickness.

Discussion

The room temperature analysis of re-expansion properties of the four densities of EPS used in the EALs of the two U.S. Army aviator helmets, shows a strong linear trend in all cases. The postcompression re-expansion slopes (figure 2) decrease with increasing density. As re-expansion is effectively complete 24 hours after compression (figure 1), investigators should wait at least 24 hours before examining damaged EALs post-accident or after laboratory based damage reconstructions. Although these samples were not compressed near instantaneously as would occur during an accident impact, EPS is not typically rate sensitive in compression and, therefore, rate of compression should have little effect on re-expansion properties. Therefore, the initial percentage EAL compression of a specific impact can be estimated using the postcompression thickness percentage and the derived equations in appendix B.

Stress and strain data recorded by the load cell were not analyzed in this study; it was not intended to estimate the force required to cause the impact compression due to the artificiality of the test. Firstly, as the samples were free-volume, radial expansion was possible during

compression. This is not the case in a fully formed EAL. Secondly, there was no outer shell interface. Therefore, a further study is proposed using current U.S. Army aviator helmets to impact test against a range of impact surfaces and at a range of drop velocities. Using the data from this current study, it will be possible to develop a series of impact force versus EAL compression nomograms for each EPS density utilized in the EALs. In turn, it will then be possible to estimate the impact forces typically encountered in survivable helicopter accidents, which will inform the debate about future levels of impact protection.

Conclusions

Re-expansion analysis data can be used to estimate the initial compression of various densities of EPS. Under room temperature conditions, EPS re-expansion is effectively complete at 24 hours and occurs in a linear way that is dependent upon EPS density.

Recommendations

Post-accident helmets should be stored at room temperature as soon as possible after recovery from an accident site, and impact analysis of the EAL should be delayed for at least 24 hours to allow for the re-expansion properties of the EPS materials.

The curves (figure 2) and equations derived (appendix C) by this research should be used routinely for both post-accident and post-impact reconstruction helmet EAL analysis.

The equations derived in this report can be used further to study other types of personal protective equipment, provided they are of the same EPS densities as those used in this study.

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Appendix A.

EPS density and helmet size matrix for the HGU-56/P AIHS.

Table A-1.
Density (g/cm^3) and size matrix for HGU-56/P EAL.

Size	Frontal Region		General Region	
	0.035 g/cm^3	0.04 g/cm^3	0.02 g/cm^3	0.035 g/cm^3
XX Small		X	X	
X Small		X	X	
Small		X	X	
Medium	X		X	
Large	X		X	
X Large	X			X

Appendix B.

EPS compression data.

Table B-1.
Definition of terms used in EPS compression data tables.

Definition of Terms Used in EPS Compression Data Tables	
Term	Definition
Density	Measured in grams per cubic centimeter
Test XX / X	Percent compression / Sample number
% Comp.	Sample compressed to X % of original thickness
BT (cm)	Baseline thickness measured in centimeters (cm)
Comp. Length	Measurement of compressed sample in cm
PCT Initial	Initial postcompression thickness measurement in cm
PCT 24 hours	Postcompression thickness measurement in cm after 24 hours
PCT 48 hours	Postcompression thickness measurement in cm after 48 hours
PCT 72 hours	Postcompression thickness measurement in cm after 72 hours

Table B-2.
0.02 g/cm^3 EPS compression data.

Density (g/cm^3)	Test	Percent Comp.	BT (cm)	Comp. Length	PCT Initial	PCT 24 hours	PCT 48 hours	PCT 72 hours
0.02	15/1	15	2.54	0.38	2.16	2.44	2.44	2.44
0.02	15/2	15	2.54	0.38	2.16	2.44	2.44	2.44
0.02	15/3	15	2.57	0.38	2.18	2.44	2.44	2.44
0.02	30/1	30	2.57	0.77	1.80	2.26	2.26	2.26
0.02	30/2	30	2.57	0.77	1.80	2.26	2.26	2.26
0.02	30/3	30	2.54	0.76	1.78	2.24	2.26	2.26
0.02	45/1	45	2.54	1.14	1.40	2.11	2.11	2.11
0.02	45/2	45	2.54	1.14	1.40	2.08	2.08	2.08
0.02	45/3	45	2.57	1.15	1.42	2.08	2.11	2.11
0.02	60/1	60	2.57	1.54	1.02	2.01	2.01	2.01
0.02	60/2	60	2.57	1.54	1.02	1.98	1.98	1.98
0.02	60/3	60	2.54	1.52	1.02	1.93	1.93	1.93
0.02	75/1	75	2.57	1.92	0.64	1.83	1.83	1.83
0.02	75/2	75	2.54	1.91	0.64	1.83	1.83	1.83
0.02	75/3	75	2.54	1.91	0.64	1.91	1.91	1.91
0.02	90/1	90	2.54	2.29	0.25	1.75	1.75	1.75
0.02	90/2	90	2.54	2.29	0.25	1.75	1.75	1.75
0.02	90/3	90	2.57	2.29	0.28	1.68	1.68	1.68

Table B-3.
0.035 g/cm^3 EPS compression data.

Density (g/cm^3)	**Test**	**Percent Comp.**	**BT (cm.)**	**Comp. Length**	**PCT Initial**	**PCT 24 hours**	**PCT 48 hours**	**PCT 72 hours**
0.035	15/1	15	2.59	0.39	2.21	2.44	2.44	2.44
0.035	15/2	15	2.59	0.38	2.21	2.44	2.44	2.44
0.035	15/3	15	2.57	0.38	2.18	2.44	2.44	2.44
0.035	30/1	30	2.62	0.78	1.83	2.26	2.26	2.26
0.035	30/2	30	2.57	0.77	1.80	2.21	2.21	2.21
0.035	30/3	30	2.57	0.76	1.80	2.18	2.21	2.21
0.035	45/1	45	2.57	1.15	1.42	1.98	1.98	1.98
0.035	45/2	45	2.57	1.14	1.42	2.01	2.01	2.01
0.035	45/3	45	2.59	1.17	1.42	1.98	2.01	2.01
0.035	60/1	60	2.59	1.55	1.04	1.80	1.80	1.80
0.035	60/2	60	2.57	1.54	1.02	1.78	1.80	1.80
0.035	60/3	60	2.59	1.55	1.04	1.78	1.78	1.78
0.035	75/1	75	2.57	1.92	0.64	1.63	1.65	1.65
0.035	75/2	75	2.57	1.92	0.64	1.65	1.65	1.65
0.035	75/3	75	2.57	1.92	0.64	1.65	1.65	1.65
0.035	90/1	90	2.62	2.35	0.25	1.40	1.40	1.40
0.035	90/2	90	2.57	2.31	0.25	1.42	1.42	1.42
0.035	90/3	90	2.59	2.33	0.25	1.40	1.40	1.40

Table B-4.
0.04 g/cm^3 EPS compression data.

Density (g/cm^3)	Test	Percent Comp.	BT (cm)	Comp. Length	PCT Initial	PCT 24 hours	PCT 48 hours	PCT 72 hours
0.04	15/1	15	2.57	0.38	2.18	2.44	2.44	2.44
0.04	15/2	15	2.57	0.38	2.18	2.44	2.44	2.44
0.04	15/3	15	2.57	0.38	2.18	2.44	2.44	2.44
0.04	30/1	30	2.62	0.00	1.83	2.21	2.21	2.21
0.04	30/2	30	2.57	0.00	1.80	2.21	2.21	2.21
0.04	30/3	30	2.57	0.76	1.80	2.24	2.24	2.24
0.04	45/1	45	2.59	0.00	1.42	1.98	1.98	1.98
0.04	45/2	45	2.59	1.17	1.42	1.98	1.98	1.98
0.04	45/3	45	2.59	1.17	1.42	1.96	1.98	1.98
0.04	60/1	60	2.57	0.00	1.02	1.73	1.73	1.73
0.04	60/2	60	2.59	0.00	1.04	1.78	1.78	1.78
0.04	60/3	60	2.57	1.55	1.02	1.75	1.78	1.78
0.04	75/1	75	2.57	0.00	0.64	1.60	1.60	1.60
0.04	75/2	75	2.57	1.93	0.64	1.63	1.63	1.63
0.04	75/3	75	2.59	0.00	0.64	1.60	1.60	1.60
0.04	90/1	90	2.59	0.00	0.25	1.37	1.37	1.37
0.04	90/2	90	2.59	2.34	0.25	1.35	1.35	1.35
0.04	90/3	90	2.59	2.34	0.25	1.40	1.40	1.40

Table B-5.
0.05 g/cm^3 EPS compression data.

Density (g/cm^3)	Test	Percent Comp.	BT (cm.)	Comp. Length	PCT Initial	PCT 24 hours	PCT 48 hours	PCT 72 hours
0.05	15/1	15	2.64	0.41	2.24	2.49	2.49	2.49
0.05	15/2	15	2.62	0.38	2.24	2.49	2.49	2.49
0.05	15/3	15	2.64	0.41	2.24	2.49	2.49	2.49
0.05	30/1	30	2.62	0.79	1.83	2.18	2.18	2.18
0.05	30/2	30	2.62	0.79	1.83	2.21	2.21	2.21
0.05	30/3	30	2.59	0.79	1.80	2.21	2.21	2.21
0.05	45/1	45	2.67	1.19	1.47	1.91	1.91	1.91
0.05	45/2	45	2.67	1.19	1.47	1.96	1.96	1.96
0.05	45/3	45	2.64	1.19	1.45	1.96	1.96	1.96
0.05	60/1	60	2.64	1.57	1.07	1.68	1.68	1.68
0.05	60/2	60	2.69	1.63	1.07	1.68	1.68	1.68
0.05	60/3	60	2.64	1.57	1.07	1.57	1.57	1.57
0.05	75/1	75	2.62	1.96	0.66	1.40	1.40	1.40
0.05	75/2	75	2.62	1.96	0.66	1.40	1.37	1.37
0.05	75/3	75	2.62	1.96	0.66	1.30	1.30	1.30

Appendix C.

Derived initial impact EAL compression equations.

EPS density (g/cm^3)	Derived equation for percent initial compression estimates ($CT_{initial}$ %) from percent postcompression thickness after 24 hours ($PCT_{>24}$ %)
0.02	$CT_{initial}\ \% = 2.73\ (PCT_{>24}\ \%) - 172.61$
0.035	$CT_{initial}\ \% = 1.91\ (PCT_{>24}\ \%) - 93.86$
0.04	$CT_{initial}\ \% = 1.81\ (PCT_{>24}\ \%) - 85.10$
0.05	$CT_{initial}\ \% = 1.40\ (PCT_{>24}\ \%) - 47.10$

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